EXHIBIT 3

ATSDR SUPPORT – ESTIMATION OF VOC REMOVAL

MARINE CORPS BASE CAMP LEJEUNE
NORTH CAROLINA

Prepared For:

ENVIRONMENTAL MANAGEMENT DIVISION
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1. INTRODUCTION

Established in 1941, the Marine Corps Base (MCB) Camp Lejeune provides specialized training to prepare troops for amphibious and land combat operations. The base is located in Eastern Onslow County, North Carolina, and it is bordered on the north by State Route 24, to the west by U.S. Route 17, and to the southeast by the Atlantic Ocean. The base occupies 246 square miles and currently houses almost 70,000 residents. The residents, commuting personnel, base visitors and contractors are served by five community water systems (CWS) and several transient, non-community water systems (TNCWS). Some of the TNCWS purchase water from Onslow County. Other systems treat ground water from on-site wells. Most of the facilities were built in the 1940s and were subsequently upgraded or rehabilitated.

1.1 PURPOSE

MCB Camp Lejeune is currently the subject of an epidemiological study by the Agency for Toxic Substance and Disease Registry (ATSDR) to ascertain the health impacts of various volatile organic chemicals (VOCs), which were present in the Hadnot Point, Tarawa Terrace and Holcomb Boulevard water supply systems in the early 1980s. The locations of these water systems are shown in Figure 1-1.

AH Environmental Consultants Inc. (AH) was retained by MCB Camp Lejeune under contract number DACW56-03-R-1013 to assist ATSDR in obtaining information required for the modeling efforts in the epidemiological study. The scope of work for the project is attached as Appendix A. This report addresses Task G, "Develop Estimates of VOC Removal Rates." As part of this effort, AH conducted a literature review and a search of the appropriate archives to assist in the development of referenced estimates of the VOC removal rates that might have occurred through the Hadnot Point, Holcomb Boulevard and Tarawa Terrace water treatment plants.
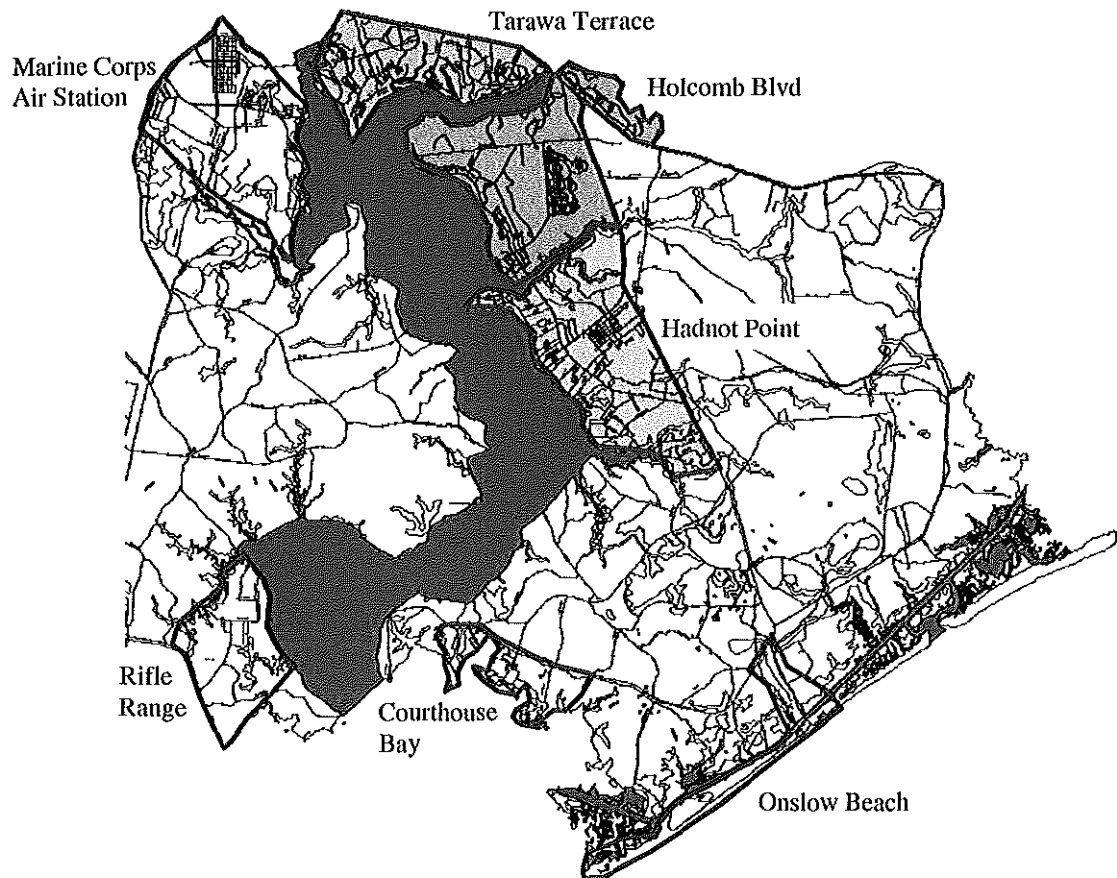
Figure 1-1. Water Systems at Camp Lejeune in the 1980s

1.2   DOCUMENT ORGANIZATION

This document is organized as follows: Section 2 provides a chronology of events relating to the groundwater contamination at the base, an account of the regulatory history involving organic compounds in drinking water and a detailed description of the Hadnot Point, Holcomb Boulevard and Tarawa Terrace water treatment plants. Section 3 provides a background on the properties of certain VOCs, their fate in water treatment processes and approaches to model their removal from aqueous solutions. Estimated removals of VOCs are presented in Section 4. The findings of this work are summarized in Section 5. Literature references are listed in Section 6.

The scope of work for this project is included in Appendix A. Dimensions of the treatment units that were in operation at the three plants are tabulated in Appendix B. Appendix C contains the detailed VOC removal calculations that are based on the models presented in Section 3.

2. BACKGROUND

This section provides a brief chronology of known events relating to the groundwater contamination at the base, an account of the regulatory history involving organic compounds in drinking water and descriptions of the Hadnot Point, Holcomb Boulevard and Tarawa Terrace water treatment plants.

2.1   CHRONOLOGY

Based on the chronology posted on the MCB Camp Lejeune website, sampling for organic contaminants in groundwater started in 1977. The initial monitoring at the water sources for Courthouse Bay, Rifle Range, Onslow Beach, Hadnot Point, Holcomb Boulevard, Tarawa Terrace, Montford Point and New River was performed for the possible presence of two herbicides (2,4-dichlorophenoxyacetic acid and 2,4,5-trichloro-phenoxypropionic acid) and four chlorinated hydrocarbons (Endrin, Lindane, Methoxychlor and Toxaphene). The detection limit was 1 µg/L for the chlorinated hydrocarbons and 0.1 µg/L for the herbicides. No contaminants were detected.

In 1982, contamination of the Hadnot Point and Tarawa Terrace water systems with Tetrachloroethylene (Perchloroethylene or PCE) and Trichloroethylene (TCE) was detected during monitoring for trihalomethanes. Subsequently, other VOCs were detected (Dichloroethylene or DCE), vinyl chloride and methylene chloride). Detection of the contamination prompted the shutdown of the contaminated wells and the continued monitoring all distributed water although a Maximum Contaminant Level (MCL) had not been established for the detected organic contaminants.

In 1982, 1983, 1984 and 1985, VOCs were detected in various drinking water wells and in finished water in the Hadnot Point, Tarawa Terrace and Holcomb Boulevard distribution system. Individual contaminated water wells were shutdown when VOC

contamination was detected. In 1988, the expansion of the Holcomb Boulevard water treatment plant was completed and the Tarawa Terrace water treatment plant was permanently shutdown. The history of water quality monitoring at the base, as last updated in July 2003, is presented on the MCB Camp Lejeune public health website.

2.2   REGULATORY HISTORY

The Safe Drinking Water Act (SDWA) (Public Law 93-523) was passed in 1974. Under the legislation of the SDWA, the United States Environmental Protection Agency (EPA) was required to set enforceable standards for health-related drinking water contaminants. These standards were to affect all public water systems serving at least 25 persons. The State of North Carolina is the primacy agency for enforcing EPA standards and has adopted all regulations promulgated under the SDWA.

The regulations of the SDWA were set in two stages: The first stage was to set interim regulations immediately. These regulations were based primarily upon the United States Public Health Service (USPHS) guidelines set in 1962. The second stage was to revise these interim regulations after an assessment of the effects of human exposure through drinking water and the toxicology of contaminants in drinking water were completed by the National Academy of Sciences. Interim standards developed in 1975 set specific maximum contaminant levels (MCLs) for several substances classified as contaminants (Table 2-1). Amendments were made to the interim standards in 1976, 1979 and 1980.

Table 2-1. Maximum Contaminant Limits for Drinking Water in 1975.

Contaminant	MCL
Organics	
Endrin	0.0002 mg/L
Lindane	0.0004 mg/L
Methoxychlor	0.1 mg/L
Toxaphene	0.005 mg/L
2,4-D	0.1 mg/L
2,4,5-TP Silvex	0.01 mg/L
Trihalomethanes	0.10 mg/L
Inorganics	
Arsenic	0.05 mg/L
Barium	1.0 mg/L
Cadmium	0.01 mg/L
Chromium	0.05 mg/L
Fluoride	1.4-2.4 mg/L
Lead	0.05 mg/L
Mercury	0.002 mg/L
Nitrate (as N)	10 mg/L
Selenium	0.01 mg/L
Silver	0.05 mg/L
Sodium and corrosion	No MCL, monitoring and reporting only
Radionuclides	
Radium 226 and radium 228	5 pCi/L
Gross alpha particle activity	15 pCi/L
Beta particle and photon radioactivity	4 mrem
Microbials	
Coliforms	<1/100 mL
Turbidity	1 TU (up to 5 TU)

In addition to the health-related enforceable standards set by the SDWA, the act mandated the USEPA to set non-enforceable federal guide-lines for contaminants that might adversely affect the aesthetic quality of drinking water. The non-enforceable federal guidelines developed into the set of initial secondary drinking water standards and their specific secondary MCLs (SMCLs). The SMCLs became effective in 1979 and are listed in Table 2-2.

Table 2-2. Secondary Maximum Contaminant Limits for Drinking Water in 1979.

Contaminant	SMCL
Chloride	250 mg/L
Color	15 color units
Copper	1 mg/L
Corrosivity	Noncorrosive
Fluoride	2 mg/L
Foaming Agents	0.5 mg/L
Iron	0.3 mg/L
Manganese	0.05 mg/L
Odor	3 (threshold odor number)
pH	6.5-8.5
Sulfate	250 mg/L
Total Dissolved Solids	500 mg/L
Zinc	5 mg/L
Proposed SCMLs	
Aluminum	0.05 mg/L
o-Dichlorobenzene	0.01 mg/L
p-Dichlorobenzene	0.005 mg/L
Ethylbenzene	0.03 mg/L
Monochlorobenzene	0.1 mg/L
Pentachlorophenol	0.03 mg/L
Silver	0.09 mg/L
Toluene	0.04 mg/L
Xylene	0.02 mg/L

The SDWA first passed in 1974 was subject to major amendments in 1986. The 1986 amendments required USEPA to set monitoring requirements for 83 drinking water contaminants by 1989 including VOCs. Originally eight VOCs were regulated under the Phase I Rule (52 FR 23690), July 1987; ten VOCs were added under Phase II (56 FR 3600), January 1991; and three VOCs were added under Phase V (51 FR 31776), July 1992. The VOCs regulated during the different phases and their MCLs are listed in Table 2-3.

Table 2-3. Volatile Organic Chemicals Regulated Under the SDWA of 1986.

Chemical	MCL (mg/L)
Phase I (1987)	
1,1,1-Trichloroethane	0.2
1,1-Dichloroethylene	0.007
1,2-Dichloroethane	0.005
Benzene	0.005
Carbon Tetrachloride	0.005
p-Dichlorobenzene	0.075
Trichloroethylene (TCE)	0.005
Vinyl Chloride	0.002
Phase II (1991)	
o-Dichlorobenzene	0.6
cis-1,2-dichloroethylene	0.07
trans-1,2-dichloroethylene	0.1
1,2-dichloropropane	0.005
Ethylbenzene	0.7
Monochlorobenzene	0.1
Styrene	0.1
Tetrachloroethylene (PCE)	0.005
Toluene	1
Xylenes (Total)	1
Phase V (1992)	
Dichloromethane	0.005
1,2,4-Trichlorobenzene	0.07
1,1,2-Trichloroethane	0.005

2.3   WATER PLANT DESCRIPTIONS

The water systems of concern in the ATSDR study, including Hadnot Point, Holcomb Boulevard and Tarawa Terrace, are described in the following sections. The descriptions are based on interviews with base personnel, site visits and an examination of design and as-built drawings that were obtained as part of this project.

2.3.1 Hadnot Point

The Hadnot Point Water Treatment Plant (WTP) (PWSID 04-670-41, Building 20) is located in a central geographic location serving the residential, commercial and industrial areas south of Wallace Creek and east of the New River. In 2001, the facility served 35,000 people and 1,050 service connections. Its current design capacity is 5.0 MGD (790 m^3/h) and treatment processes include chlorine disinfection, lime softening with spiractors, followed by filtration, and fluoridation.

The Hadnot Point WTP was designed in 1941/1942 by Carr & J.E. Greiner Co. for the Marine Barracks New River, North Carolina under a contract with the U.S. Navy Bureau of Yards and Docks (M.B. Project No. P-108-4). As originally built, groundwater was treated in three parallel pellet reactors ("spiractors") with a capacity of 700 gpm (158 m^3/h) each, where lime slurry was added for softening. The water was discharged into a 17,000-gallon (64.3 m^3) recarbonation basin (Figure 2-1) and then distributed onto three parallel dual-media gravity filters (Figure 2-2). The filter media consisted of a 27-inch (0.69 m) layer of sand on top of an 18-inch (0.45 m) layer of gravel. Disinfection was accomplished using two gas chlorinators. The chlorine solution could be injected at three different points upstream of the spiractors and downstream of the filters. Finished water was then discharged into an 800,000-gallon (3,000 m^3) clearwell.

Based on a design by Carr & J.E. Greiner Co., the plant underwent a major expansion in 1944/1945. Under Project P-1517, two spiractors, two filters and an additional 560,000-gallon (2,100 m^3) clearwell were added to the plant to obtain today's capacity of 5 MGD. A third finished water reservoir with a capacity of 2 million gallons (7,600 m^3) was added to plant in the early 1950s. The last major change in the configuration of the Hadnot Point WTP until the 1980s occurred in 1959-1961, when the 800,000-gallon (3,000 m^3) clearwell was converted into a raw water reservoir by L.E. Wooten & Company under a contract with the U.S. Navy Bureau of Yards and Docks.
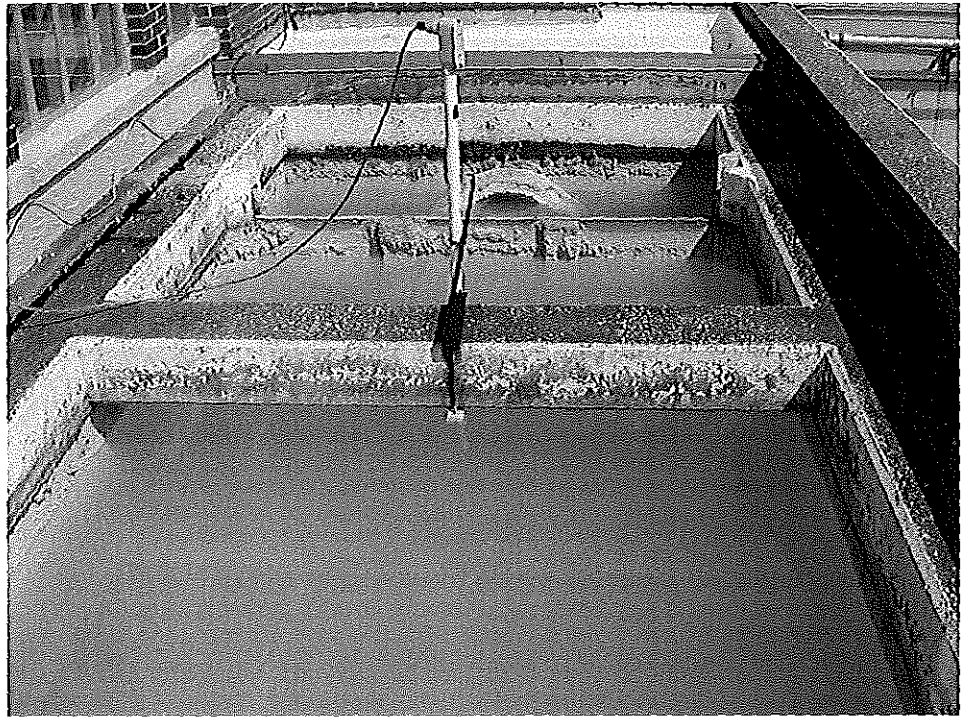
Figure 2-1. Hadnot Point WTP Recarbonation Basin.

Figure 2-2. Hadnot Point WTP Filter.

At some unknown time in the past decades, the plant operators discontinued recarbonation. However, softened water still flowed through the basin. The plant configuration during the period from 1968–1985 is depicted in Figure 2-3.
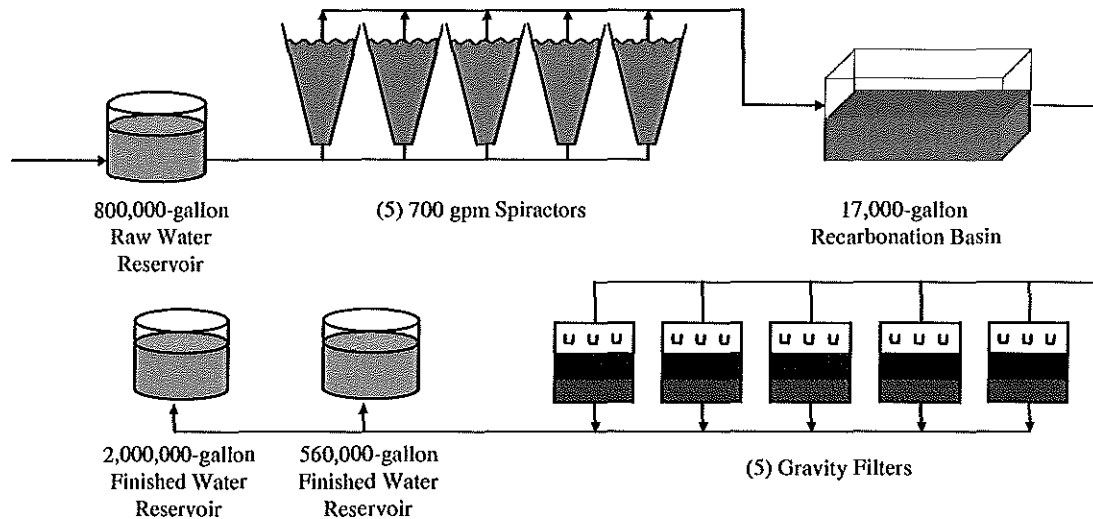
Figure 2-3. Hadnot Point Water Treatment Plant 1968-1985.

2.3.2 Holcomb Boulevard

The Holcomb Boulevard WTP (PWSID 04-67-043, Building 670) supplies water to the central geographic area north of Wallace Creek, Tarawa Terrace (since 1988), U.S. Naval Hospital, Midway Park and Camp Johnson. In 2001, the facility served 17,000 people and 1,500 service connections. Today, its design capacity is 5.0 MGD (790 m^3/h) and the treatment processes include chlorine disinfection, lime softening with spiractors, followed by filtration, and fluoridation.

The Holcomb Boulevard WTP was constructed in the early 1970s based on a design by Henry von Oesen & Associates on a contract with the Naval Facilities Engineering Command, Atlantic Division (LANTDIV). Originally designed for a capacity of 2

MGD (315 m³/h), the plant was equipped with two parallel 700 gpm (158 m³/h) spiractors for lime softening (Figure 2-4). There was no recarbonation basin and the water discharged directly to two dual-media gravity filters. The filter media consisted of 12 inches (0.30 m) of gravel and 27 inches (0.69 m) of sand. Filtered water flowed to a clearwell with a capacity of 1 million gallons (3,800 m³). The plant configuration during the period from 1970–1985 is depicted in Figure 2-5.

The plant underwent its first major upgrade in 1984-1987 under LANTDIV contract No. N62470-81-B-1644. During this period, its capacity was expanded to its current capacity of 5 MGD (19,000 m³/d) by adding three spiractors and three gravity filters. In addition, two circular tanks, one for raw water and one for finished water storage, were added to the plant. The raw and finished water reservoirs each had a capacity of 2 million gallons (7,600 m³).
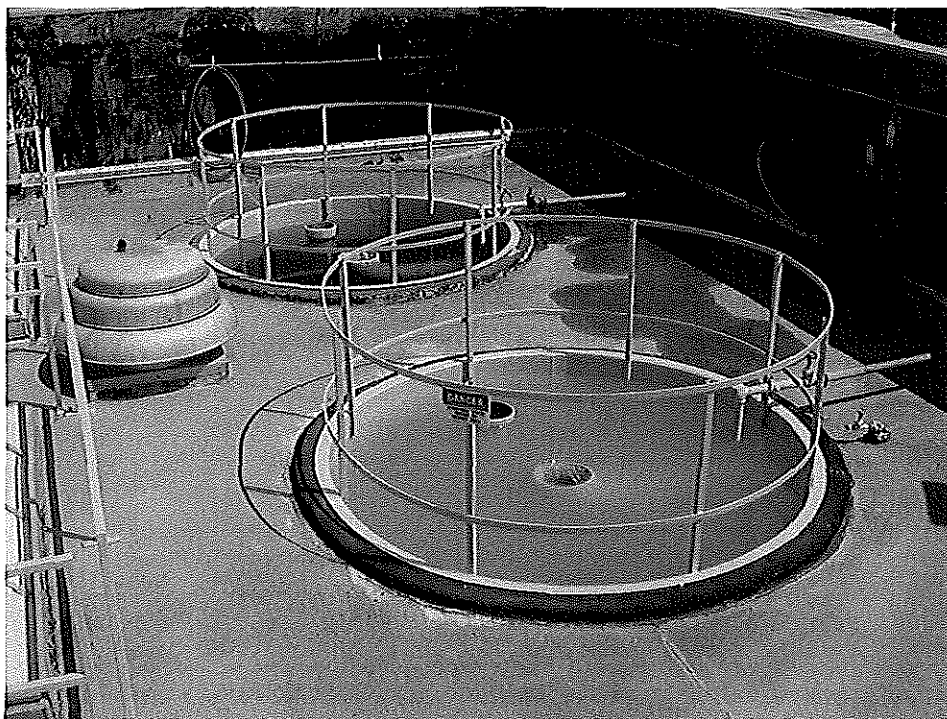
Figure 2-4. Holcomb Boulevard WTP Spiractors.

| | | 1,000,000-gallon
Finished Water |
| (2) 700 gpm Spiractors | (2) Gravity Filters | Reservoir |
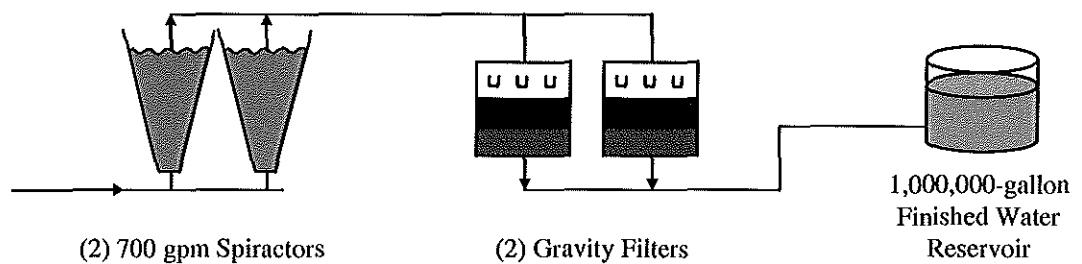
Figure 2-5. Holcomb Boulevard Water Treatment Plant 1970-1985.

2.3.3 Tarawa Terrace

The Tarawa Terrace WTP served a population of 6,300 until it was shutdown in 1988 after the Holcomb Boulevard plant expansion was completed. Its design capacity was 1 MGD (158 m^3/h) and treatment processes included chlorine disinfection, lime softening with spiractors (pellet reactors), followed by filtration and fluoridation.

The earliest available design drawings suggest that the plant was built in the early 1950s. These drawings did not agree with designs for later upgrades. However, based on as-built drawings for a water supply improvement project in 1963 (Bureau of Yards and Docks No. 859315 – 859320), it appears that the plant was equipped as follows: Raw water was pumped directly from the supply wells to a single 700 gpm (158 m^3/h) spiractor for lime softening. The softened water was then conveyed to six parallel 9-foot diameter pressure filters, two of which were added during the 1963 upgrade project. Filtered water was collected in a 750,000-gallon (2,800 m^3) clearwell and pumped to a 12-inch distribution system header using up to four pumps with capacities of 500 gpm, 750 gpm, 1000 gpm and 1250 gpm. The plant configuration during the period from 1968–1985 is shown in Figure 2-6.

(1) 700 gpm Spiractor   (6) Pressure Filters   750,000-gallon Finished Water Reservoir
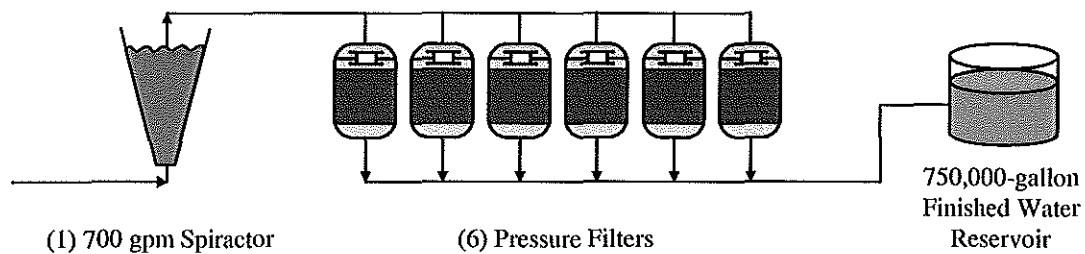
Figure 2-6. Tarawa Terrace Water Treatment Plant 1968-1988.

Operation of the Tarawa Terrace WTP was discontinued in 1988, when the Holcomb Boulevard WTP expansion was completed and the distribution systems were interconnected.

3. MODELING VOC REMOVAL

This section provides a background on the properties of certain VOCs, their fate in water treatment processes and approaches to model their removal from aqueous solutions.
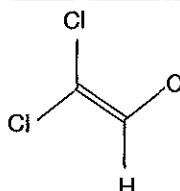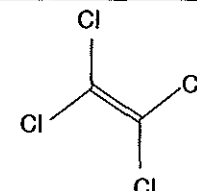
3.1 PROPERTIES OF TRICHLOROETHYLENE AND TETRACHLOROETHYLENE

Five VOCs were identified as contaminants in the Camp Lejeune's wells and finished water: TCE, DCE, PCE, methylene chloride and vinyl chloride. The two specific VOCs that are part of ATSDR's computer modeling of the MCB water system over the period of 1968-1985 are TCE and PCE.

Trichloroethylene (TCE) is a nonflammable, colorless liquid with a somewhat sweet odor and a sweet, burning taste. It is used mainly as a solvent to remove grease from metal parts, but it is also an ingredient in adhesives, paint removers, typewriter correction fluids and spot removers. Tetrachloroethylene (PCE) is a chemical that is widely used for dry cleaning of fabrics and for metal-degreasing. It is also used to make other chemicals and is used in some consumer products. It is a nonflammable liquid at room temperature, evaporates easily into the air and has a sharp, sweet odor. Some physical and chemical properties of these two compounds are summarized in Table 3-1. Estimated Henry's Law constants and diffusion coefficients were obtained from EPA (2004).

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Table 3-1. Physical and Chemical Properties of TCE and PCE.

Property (at 20 °C, 1 atm)	TCE	PCE
CAS Registry Number	79-01-6	127-18-4
Name (according to NIST Standard Reference Database 69)	Trichloroethylene	Tetrachloroethylene
Molecular Formula	C_2HCl_3	C_2Cl_4
Structural Formula		
Molecular Weight	131.39	165.82
Henry's Constant (atm·m^3/mol)	7.07×10^{-3}	1.31×10^{-2}
Diffusion Coefficient in Water (cm^2/s)	8.43×10^{-6}	7.59×10^{-6}
Diffusion Coefficient in Air (cm^2/s)	0.0890	0.0813

3.2 FATE OF VOLATILE ORGANIC COMPOUNDS

In reviewing the fate of VOCs that have contaminated bodies of water, volatilization has been shown to be a significant pathway for loss across the air-water interface. This is especially true for organic pollutants whose Henry's constants are greater than 4.6×10^{-3} atm·m^3/mol (Smith *et al.*, 1980). For highly volatile solutes (high Henry's constants) volatilization loss has been shown to be enhanced by air turbulence and sub-water mixing (Chiou *et al.*, 1980). Callaghan *et al.* (1979), summarizing in an EPA report on the fate of priority pollutants in aqueous systems, recognized volatilization as the primary transport process for VOCs (e.g., TCE, DCE, PCE).

As far back as the 1970s, volatilization of man-made chlorinated hydrocarbons throughout the global environment and its subsequent contamination has led researchers to develop mathematical expressions to predict the transfer of contaminants from water to air. Mackay and Leinonen (1975) presented equations to predict the rate of evaporation of organic contaminants (i.e., VOC) from water bodies to the atmosphere.

Dilling (1977) measured half-lives for evaporation of organic chemicals from dilute aqueous solutions (1 mg/L) from an average solution depth of 2.5 in (6.5 cm), under quiescent air conditions while stirring at 200 rpm at 25°C. Evaporation half-lives for organic chemicals ranged from 17 to 56 minutes. For TCE and PCE, Dilling *et al.* (1975) presented data showing that volatilization of 50% of the two compounds from a dilute solution (1 mg/L) occurred in less than 30 minutes and 90% volatilization occurred in less than 90 minutes. The authors suggested that the VOCs will not persist in natural water bodies due to evaporation. In a study on persistence of organic chemicals in natural water bodies, volatilization was considered the major process of removal of organic contaminants from surface waters (Zoeteman *et al.*, 1980). Half-lives of organic chemicals in surface water bodies have been reported on the order of 1-10 days (Zoeteman *et al.*, 1980). Callaghan *et al.* (1979) and references therein, cautioned against extrapolating volatilization results from laboratory studies considering that surface and bulk agitation can be highly variable in natural waters.

Peng *et al.* (1994) estimated the volatilization rate constant of dissolved volatile organic compounds (TCE, PCE) from a 1000 mL beaker in the laboratory under near ideal quiescent conditions. The volatilization rate constant from this model was found to be inversely proportional to the square of the water depth under ideal quiescent conditions whereas it was proportional to the inverse of the depth under completely mixed conditions. A theoretical and a simplified model were applied to experimental data and correlation coefficients of better than 0.95 were obtained for all tested cases. Near quiescent experimental conditions are expected to prevail in water treatment holding/storage tanks.

Surveys of VOC occurrence in groundwater (Squillace, 1999) and evaluations of VOC treatment technologies for drinking water (Love and Eilers, 1982) have stated that incidental removal of VOC is likely to occur during conventional water treatment through aeration/volatilization, although conventional water treatment processes have

been shown to be ineffective in directly reducing concentrations of VOCs in a contaminated raw source water (Love *et al.*, 1983).

In wastewater treatment, VOC emissions have been thoroughly studied. Models have been developed to estimate emissions of organic compounds through various pathways including volatilization. An EPA report (EPA, 1980), assessing innovative and alternative technology in wastewater treatment, stated that hydraulic jumps, overflow weirs, open clarifier surfaces, operations that cascade the water, finished water storage, all provide opportunities for potential loss of VOCs from water. Such VOC removals are the result of happenstance rather than optimized design to provide maximum removal, as in air stripping treatment processes.

Volatilization in the form of VOC emissions from various industrial unit processes including wastewater treatments has been studied by Tansel and Eyma (1999) who developed mathematical models to estimate mass transfer for volatilization from clarifier surfaces and weirs as well as aeration basins. Tansel and Eyma (1999), and references therein, found that VOC emissions were dependent on the air-water surface area, degree of agitation of the water surface and the residence time of the water in the tanks. During the development of the VOC emission model, it was assumed that volatilization was the single most important removal mechanism for the VOCs under study, including TCE and PCE, that were detected in the influent streams at concentrations of 3.75 µg/L and 8.7 µg/L, respectively. Removal rates were on the order of 68% for TCE and 86% for PCE with most of the volatilization occurring from the aeration tanks and weirs. Nakasone (1986) also modeled VOC removal during aeration at weirs and cascades and incorporated terms for fall-height, discharge and tail water depth.

3.3 OVERVIEW OF VOLATILIZATION MODELS

A summary of the existing models for the volatilization of organics from water bodies (e.g., rivers and lakes) was provided by Thomas (1990). He evaluated four different approaches:

- Method of Mackay and Wolkoff (1973): This method is based on thermody-namic considerations and applicable to only a restricted class of compounds. The method is not recommended for general use. It was later expanded according to the methods developed by Liss and Slater (1974).

- Method of Liss and Slater (1974): The volatilization is modeled as a two layer film where at the interface, the ratio of concentration across air to water is assumed to equal Henry's law constant. Transfer through the films occurs through molecular diffusion. The resulting mass transfer coefficients are empirical in nature.

- Method of Chiou and Feed (1977, 1979): The method is based on gas dynamics and thermodynamic considerations. It was not adopted in later studies of volatilization of organic chemicals from water.

- Method of Smith et al., (1980): This method is based on reaeration and is applicable to compounds with high Henry's constants and low solubility.

The method recommended by Thomas (1990) follows the two-film concept introduced by Liss and Slater (1974) and extended by Mackay and Leinonen (1975). Liss and Slater's model was also adopted for the Estimation Program Interface (EPI), a suite of environmental fate estimation models developed for the EPA Office of Pollution Prevention Toxics by the Syracuse Research Corporation (SRC). Using a single input, EPI calculates the VOC volatilization from rivers and lakes and half-lives among other physical–chemical properties and environmental fate parameters.

EPA's Office of Air Quality Planning and Standards (OAQPS) has developed a computer program WATER9 (which superseded an earlier WATER8 version), for estimating the loss of organic compounds through volatilization from various wastewater treatment units including overflow weirs (EPA, 1994). Equations used in WATER9 along with examples are provided in the program manual (EPA, 1994). Nakasone's (1986) model for weir aeration has been adopted in the WATER9 program for estimating VOC loss from a weir.

3.4   ESTIMATION OF VOC EMISSIONS FROM WATER TREATMENT UNITS

In this work, the estimation of volatilization half-lives of TCE and PCE and their re-
moval rates from various water treatment units was made based on the series of equa-
tions compiled by Thomas (1990). Volatilization depends on the chemical properties
of the organic compound under study (e.g., solubility, vapor pressure, Henry's law
constant) and the physical characteristics of the water body (e.g. depth, flow rate).

The following water treatment units were evaluated with respect to their contribution
to the volatilization of TCE and PCE from air-water interfaces:

- Raw water reservoir
- Recarbonation basin
- Filter water surfaces
- Spiractors water surfaces
- Overflow weirs in spiractors
- Finished water storage reservoirs

The model of Mackay and Leinonen (1975) as outlined in Thomas (1990) was used to
estimate half-lives and VOC removal rates from the above treatment water holding
structures. Nakasone's (1986) model as adopted in the EPA's WATER9 model was
used to calculate VOC removal from spiractor weirs. Detailed mathematical descrip-
tions of the models are provided in the following sections. The dimensions of various
treatment units were obtained from schematics provided by MCB Camp Lejeune for
WTP structures that were in existence up to 1985.

The spiractors at the three treatment plants were identical in capacity and dimensions.
In the model, removal of VOC occurred from the top surface as shown in Figure 3-1
as well as from the nappe (i.e., the sheet of water falling over a weir) believed to be
formed at the center effluent pipe.

$\varnothing 10.4$ ft (3.2 m)

VOC

22 ft (6.7 m)

$\varnothing$ 2.4 ft (0.7 m)
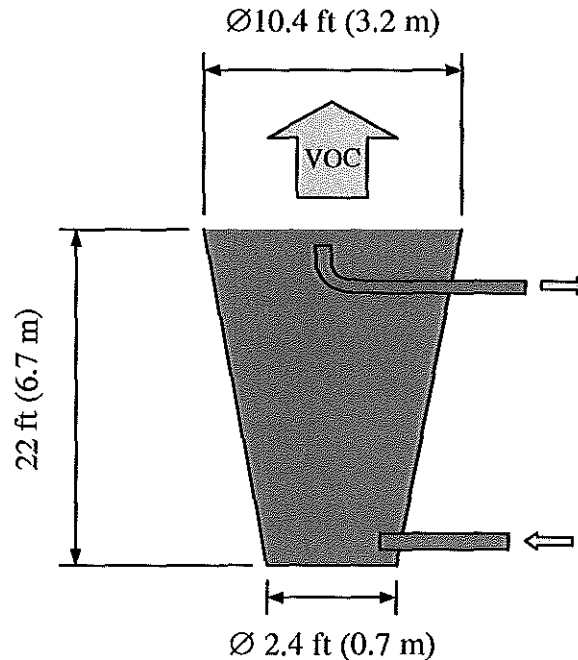
Figure 3-1. Spiractor Dimensions.

Images of the pipes at the Hadnot Point WTP are provided in Figure 3-2 and Figure 3-3. A detailed sketch of the effluent pipe is shown in Figure 3-4. The input parameters needed to estimate the VOC removal from a weir using Nakasone's model were determined as follows: the depth over the circular pipe (H_c) was estimated using Francis' weir equation and assuming that the pipe represents a sharp-crested weir with a length equal to the circumference of the pipe. The fall height was estimated visually based on recent photographs. An approximation for the tail water depth was obtained by assuming that critical flow occurs downstream of the bend. The critical depth for a circular 12-inch pipe at a flow rate of 1 MGD (158 m^3/h) is approximately 6 inches (0.12 m).

The dimension of the water storage tanks and filters are listed in Appendix B. For the calculation of VOC removals, the overflow and the bottom elevations of the basins and tanks were used to determine the water depth. For filters, only the water depth

above the granular media was taken into account. The normal water elevation was determined from the elevations of shut-off floats or overflows.
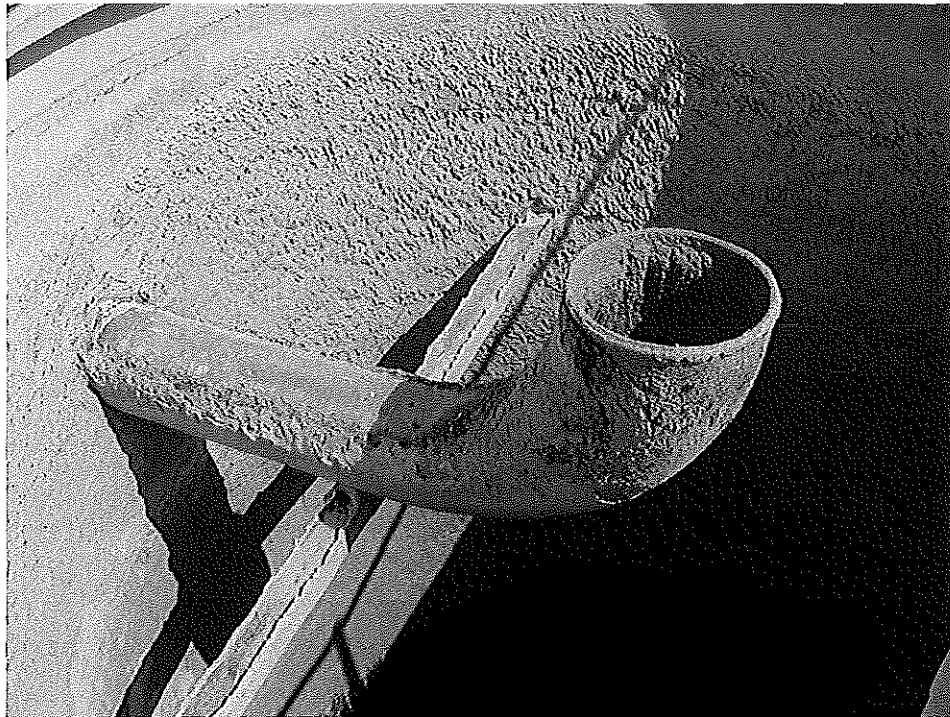
Figure 3-2. Hadnot Point WTP Spiractor Effluent Pipe (1941/1942).

Figure 3-3. Hadnot Point WTP Spiractor Effluent Pipe (1944/1945).
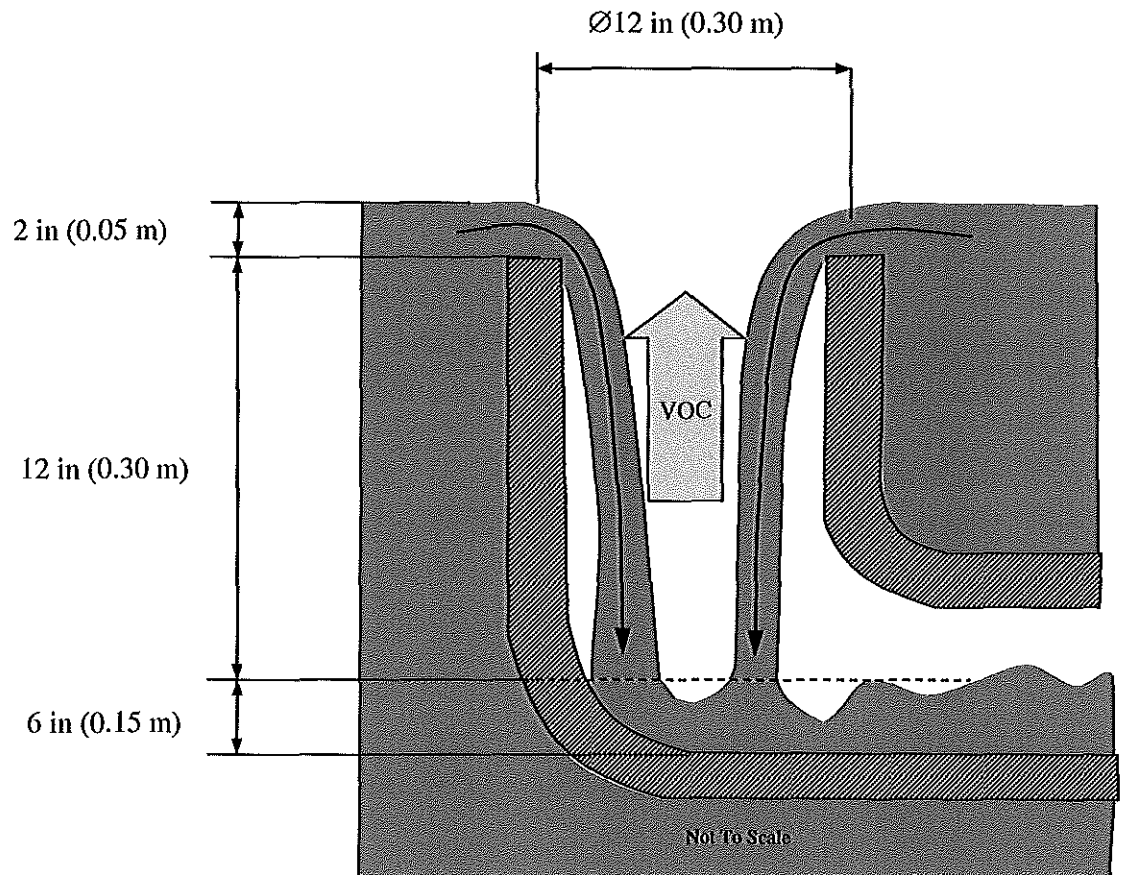
Figure 3-4. VOC Removal Due to Aeration at Effluent Pipe.

3.4.1 VOC Removal from Quiescent Basins with Flow

Raw and finished water reservoirs and any other water holding structure exhibiting a large surface area would be conducive for volatilization of VOCs from the open liquid surface into the air. The modeling of the volatilization rates is based on the chemical properties of the contaminants (i.e., TCE and PCE) identified in the water entering the three WTPs and on the physical properties of the unit processes (i.e., dimensions, flow rate).

Although the errors associated with these types of calculations are unknown, it is generally believed that estimates of volatilization are in agreement with actual processes

within a factor of ten and probably within a factor of two or three in most cases (Thomas, 1990).

In a quiescent tank (e.g., raw and finished water reservoirs, filter beds and spiractors) the water is assumed to be well mixed and the bulk concentration of a contaminant is equal to the effluent concentration and can be estimated from a material balance. VOC volatilization is a first-order rate process and the remaining fraction of a chemical can be expressed as follows:

$$\frac{C_o}{C_i} = \exp(-k_v t)$$

Equation 1

C_o is the effluent concentration, C_i is the influent concentration, k_v is the overall volatilization rate constant and t represents the residence or detention time in the reactor. The detention time is calculated by dividing the reactor volume by the flow rate. The decay of the chemical is an exponential function of time as shown in Figure 3-5.
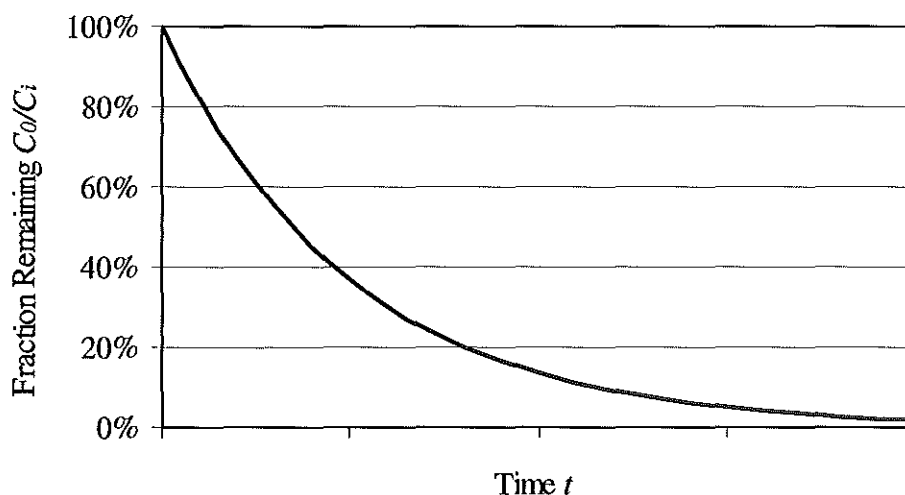
Figure 3-5. Exponential Decay Due to Volatilization.

The overall volatilization constant, k_v, depends on the overall liquid mass transfer coefficient, K_L, and the mean depth of the water body, Z:

$$k_v = \frac{K_L}{Z} \qquad \text{Equation 2}$$

The overall liquid mass transfer coefficient, K_L, needed to solve Equation 1 is estimated from a two-phase resistance model as follows:

$$K_L = \frac{\left(\dfrac{H}{RT}\right)k_g k_l}{\left(\dfrac{H}{RT}\right)k_g + k_l} \qquad \text{Equation 3}$$

The additional unknowns introduced in Equation 3 include the liquid-phase mass transfer coefficient, k_l, and the gas-phase mass transfer coefficient, k_g. RT is the product of the universal molar gas constant and the absolute temperature which has a numerical value of 0.024 atm·m^3/mol at 20 °C. H is the substance-specific Henry's Law constant.

The transfer coefficients k_l and k_g depend on wind and/or water velocity, water depth, Z, and molecular weight, M, of the chemical:

$$k_g = 1137.5 \cdot \left(V_{wind} + V_{water}\right) \cdot \sqrt{\frac{18}{M}} \qquad \text{Equation 4}$$

$$k_l = 23.51 \cdot \left(\frac{V_{water}^{0.969}}{Z^{0.673}}\right) \cdot \sqrt{\frac{32}{M}} \qquad \text{Equation 5}$$

For raw and finished water reservoirs, the water velocity can be computed by dividing the flow rate by the cross-sectional area. In filters and spiractors, the overflow rate, i.e., the quotient of flow rate and surface area can be used. If the wind velocity ex-

ceeds 1.9 m/s, then the following equation should be used for the liquid mass transfer coefficient:

$$k_l = 23.51 \cdot \left(\frac{V_{water}^{0.969}}{Z^{0.673}} \right) \cdot \sqrt{\frac{32}{M}} \cdot \exp(V_{wind} - 1.9) \qquad \text{Equation 6}$$

Average wind speeds in coastal regions in North Carolina range from 8 to 12 mph (3.6 to 5.4 m/s) (National Climatic Data Center, 1998). A wind velocity of 5 m/s was used to compute the volatilization from the spiractors and the recarbonation basin. The other treatment components are covered or indoors.

3.4.2   VOC Removal from Weir Structures

In addition to surface volatilization, the spiractor effluent pipe offers a weir like structure through which water is transferred to the filter beds. According to Nakasone's (1987) model as implemented in WATER9 (EPA, 1994), volatilization to air over weir type structures is a function of flow rate, fall distance and tail water depth. The fraction of a chemical that is removed, C_o/C_i, is estimated by the following relationship:

$$\frac{C_o}{C_i} = \exp\left(-\frac{K_o Z}{q} \right) \qquad \text{Equation 7}$$

K_o is the overall mass transfer coefficient based on the liquid concentrations, q is the water flow rate per length of the weir and Z is the fall height including 1.5 times the distance from the weir top to the critical depth above the weir. The value of the overall mass transfer is estimated from the liquid and gas mass transfer coefficients, k_l and k_g, and Henry's constant, H, as shown in Equation 8.

$$K_o = \left(\frac{1}{k_l} + \frac{RT}{k_g H} \right)^{-1}$$

Equation 8

The gas mass transfer coefficient of the flow at the weir is estimated using Equation 9, where D_{gv} is the diffusion coefficient of the organic chemical in air and D_{go} the diffusion coefficient of a reference substance (benzene, D_{go} = 0.0982 cm^2/s).

$$k_g = 0.05 \cdot \left(\frac{D_{gv}}{D_{go}} \right)^{0.66}$$

Equation 9

A value of the liquid phase mass transfer coefficient can be estimated for organics, after correcting for the relative diffusion coefficient of the organic and oxygen in water.

$$k_l = \frac{q}{Z} \left(\frac{D_{lv}}{D_{lo}} \right)^{0.66} \ln(r)$$

Equation 10

D_{lv} is the diffusion coefficient of the organic chemical in water and D_{lo} the diffusion coefficient of the reference substance, benzene, in water (D_{lo} = 8.99 $\times$ 10^{-6}). $\ln(r)$ is the deficit ratio for the compound of interest, which is computed according to Equation 11, where h is the tail water depth at the weir.

$$\ln(r) = 0.0785 \cdot Z^{1.31} q^{0.428} h^{0.13}$$

Equation 11

4. RESULTS

Using the model presented in the previous sections, fractional removals of TCE and PCE from the treatment units that existed at the Hadnot Point, Holcomb Boulevard and Tarawa Terrace WTPs were estimated. Detailed calculations are included in Appendix C in the same order as presented below. All computations were based on a temperature of 20 °C and atmospheric pressure of 1 atm (101.325 kPa).

4.1 VOC REMOVAL FROM SPIRACTORS

To determine the fractional VOC removal from spiractors, only a single computation is necessary because the spiractors used at the three plants are identical and operate under the same design conditions. That is, for example, the fractional VOC removal in five spiractors operating at 5 MGD is equal to that in one spiractor operating at 1 MGD.

The calculations reveal that the removal of TCE and PCE by volatilization from the water surface in the spiractors is virtually zero. The half-life of these compounds, i.e., the time required for 50% removal, is approximately 200 days, whereas the detention time in the reactors is less than 10 minutes. The presence of wind at a speed of 5 m/s has no significant effect on the removal within the reactor due to the short detention time.

4.2 VOC REMOVAL FROM WEIR STRUCTURES

Using Nakasone's model as implemented in WATER9, volatilization due to aeration at the spiractor effluent pipe resulted in TCE and PCE removals of 6.1% and 7.7% at the design flow rate 700 gpm, respectively. These moderate removals are due to the turbulence created by the nappe upon impacting the horizontal pipe section.

A sensitivity analysis showed that the fall height has the largest effect on VOC removal at a weir. It was found that the removal of PCE and TCE is nearly proportional to the fall height. Observations on-site indicated the fall height can be highly variable depending on downstream head conditions, for example, due to filter backwashing. This variability is illustrated in pictures taken at the Hadnot Point WTP. Only a small vortex formed over the submerged effluent pipe (Figure 4-1) on one spiractor and then developed a nappe after a backwashed filter went back online (Figure 4-2). Because of the downstream recarbonation basin at that plant, the available head does not appear to allow a fall height of greater than approximately one foot and the effluent pipe is likely to be flowing full. However, at the Holcomb Boulevard WTP, because of the absence of a recarbonation basin, water falls approximately two feet to the bottom of the horizontal pipe section, allowing violent mixing and open channel flow (Figure 4-3).
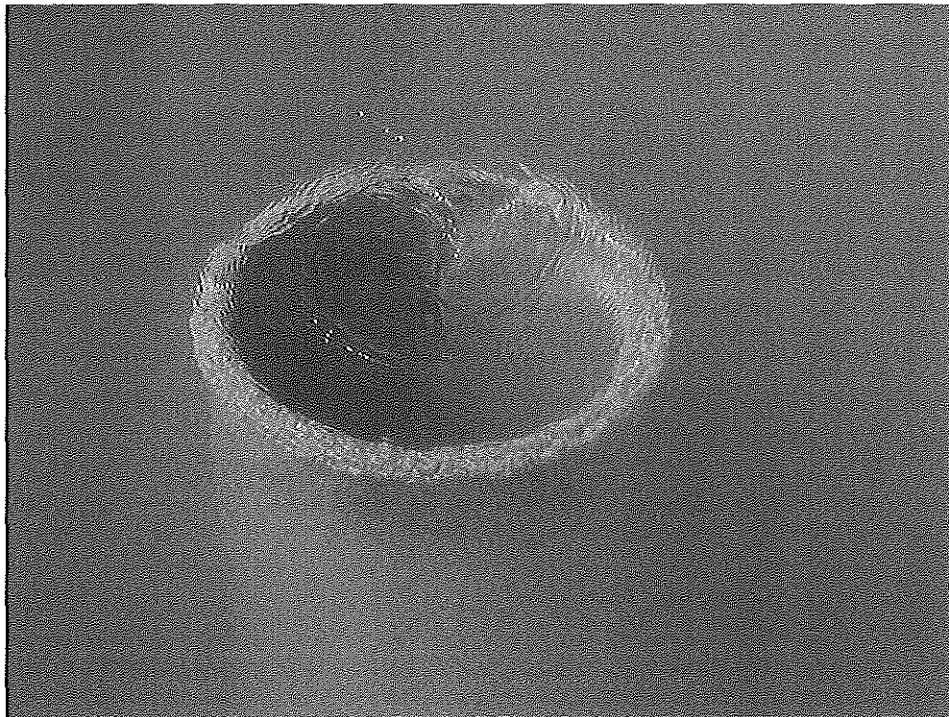
Figure 4-1. Vortex Over Hadnot Point WTP Spiractor Effluent Pipe.
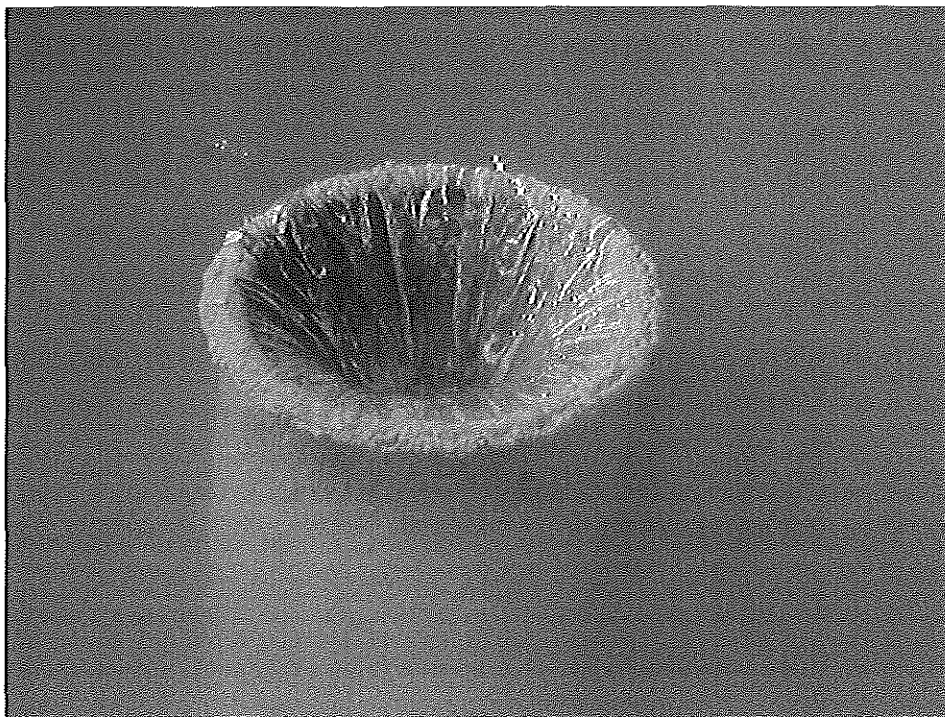
Figure 4-2. Nappe Developed at Hadnot Point WTP Spiractor Effluent Pipe.
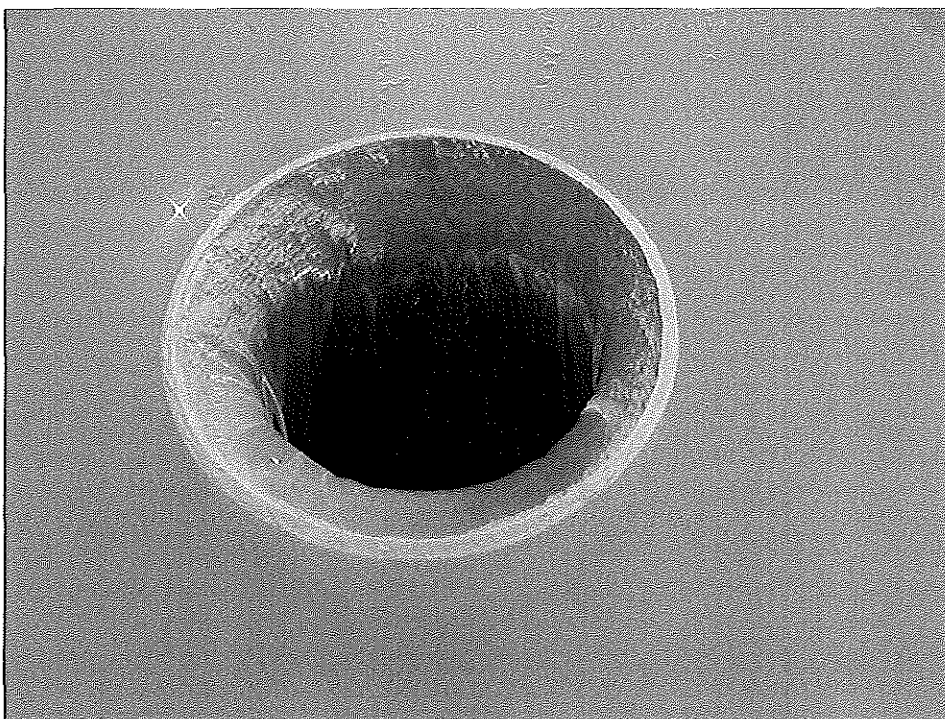
Figure 4-3. Fall Height at Holcomb Boulevard WTP Spiractor Effluent Pipe.

Based on these observations, there is some uncertainty in the removal estimates from the effluent pipes. Additional uncertainties are introduced by varying head losses in the pipes caused by calcium carbonate scale built-up and manual cleaning. However, it is estimated that PCE and TCE removals due to aeration at the spiractor effluent pipes are likely to be no larger than 15%.

4.3 VOC REMOVAL FROM RESERVOIRS AND FILTERS

In raw and finished water reservoirs, the flow velocity was calculated based on the vertical cross-sectional area. For filters, the overflow rate was used as an estimate of the velocity. In both cases, the wind speed was neglected because the reservoirs are covered and the filters are located within the operations buildings.

TCE and PCE removals from the filters were virtually zero. Due to the exposure to wind, fractional removals from the recarbonation basin were discernible (0.03%) but too small to be considered significant. Despite the large surface areas, VOC removals in the raw and finished water reservoirs, ranging from 0.01% to 0.04%, were also negligible.

In all cases, the effect of flow restrictions at basin inlets and outlets on the velocity was not taken into account. Considering such effects would require the development of a detailed hydrodynamic model for each basin. However, calculations with an order-of-magnitude variation in flow velocity showed that it is unlikely that localized higher velocity could have significantly affected the VOC removal in the basins.

5. SUMMARY

MCB Camp Lejeune is currently the subject of an epidemiological study by the ATSDR to ascertain the health impacts of certain VOCs, including TCE and PCE which were present in the Hadnot Point, Tarawa Terrace and Holcomb Boulevard water supply systems in the early 1980s. AH assisted in the development of referenced estimates of the VOC removal rates that might have occurred within the treatment units that existed at the three plants during 1968-1985.

After determining the configuration and dimensions of the water treatment units in the three locations and after reviewing applicable models for estimating the volatilization rates of organic chemicals from water, TCE and PCE removals were calculated for raw and finished water reservoirs, recarbonation basins, filters and spiractors.

The calculations revealed that VOC removal due to volatilization from quiescent basins was negligible at MCB Camp Lejeune. The only significant VOC removals must have occurred at the spiractor effluent pipe, where the falling water undergoes some aeration. Considering the uncertainty in the estimates for the fall height over the weir formed by the pipe, the removals for TCE and PCE were likely to be less than 15%.

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APPENDIX A

SCOPE OF WORK

AH Environmental Consultants

SCOPE OF WORK
WATER MODELING SUPPORT

I.   BACKGROUND

    A.   Camp Lejeune is currently the subject of an epidemiological study by the Agency for Toxic Substance and Disease Registry (ATSDR) to ascertain the health impacts of various chemicals, which were present in the Hadnot Point, Tarawa Terrace, and Holcomb Boulevard water supply systems in the early 1980's.

II. OBJECTIVE

    A.   The primary objective of this project is to assist ATSDR in obtaining the historical and current information required for the modeling efforts that will be used in ATSDR's epidemiological study.

III. SPECIFIC TASKS

    A.   The consultant shall develop a chronology of infrastructure changes within the Tarawa Terrace, Holcomb Blvd, and Hadnot Point water distribution systems from 1968 to 1985. This chronology shall consist of a summary of relevant construction and maintenance projects and resulting modifications to infrastructure

    B.   The consultant shall develop GIS maps illustrating water treatment and distribution systems (TT, HB, HP) infrastructure corresponding to stages of their evolution from 1968 to 1985. These maps should reflect changes to the water main system (typically pipes over 2" in diameter) on an annual basis. These maps shall show locations and attributes of all components, including water mains (material and sizes), valves, hydrants, and blowoffs. The year installed and retired (if applicable) shall be noted in the attribute tables.

    C.   The consultant shall develop a Water System Report to support the water system modeling effort. The report shall include the following:

        a. Data on dates that the water supply wells were installed and closed.

        b. Detailed description of the Tarawa Terrace Water Treatment Plant, which includes capacity, storage tank sizes and locations, booster pump sizes and

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configurations, treatment process descriptions, etc.

D. The consultant shall provide contaminant occurrence, fate and transport assistance to ATSDR.

E. The consultant shall provide up to 3 staff to attend up to 5 meetings at MCB Camp Lejeune.

F. The consultant will conduct a literature review and a search of the appropriate archives to develop referenced estimates of the VOC removals that might have occurred through the Hadnot Point, Holcomb Boulevard and Tarawa Terrace water systems.

G. The consultant shall provide the following support to ATSDRs distribution system tracer study efforts: a) Review ATSDRs draft Work Plan for the Tracer Study – Preliminary Test; b)Provide up to 2 days of onsite assistance during the preliminary test; c) Review ATSDRs draft Work Plan for the Tracer Study – Full Scale Test; b)Provide up to 4 days of onsite assistance during the Full Scale Test.

H. *The consultant shall keep detailed records of the number of hours that employees work to reseach archival records and digitize historical water system maps.*

I. *The consultant shall evaluate and provide a summary of the state of the technology for gas chromatographs in the early 1980's. The summary should evaluate the availability, use, limitations, and accuracy of GC technology as applied to water quality testing, specifically TTHM testing.*

J. *The consultant shall review the lab notes provided by Grainger Laboratory. The notes were made in the context of monitoring for TTHM's in drinking water. Describe the laboratory procedures for analyzing TTHM's at the time, including how "interference" from hydrocarbons would have been detected and how the interference would have affected the results. Describe the quantitative conclusions,results and accuracy regarding VOC's that the lab personnel would/could have drawn from the test results. Provide an opinion as to the context of these notes in terms of the presence of VOC's in the water tested.*

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VI. MILESTONES AND MEETINGS

A. The Contractor shall comply with the schedule of milestones, meetings, and submittal dates that will be established in consultation with Camp Lejeune and ATSDR. All meetings will be at Camp Lejeune unless otherwise requested by Camp Lejeune or ATSDR.

The contractor shall coordinate all work with MCB Base Utilities and Public Works Office. A schedule of work shall be submitted to the POC at least 7 days prior to the beginning of work. Two days prior to the start of the work, the contractor shall contact the MCB Base POC to confirm the schedule. Any changes in the schedule must be coordinated with the MCB Base POC.

V. SUBMITTALS

A. Reports

1. The A/E shall submit five copies of the draft report and three electronic copies of the report on Tasks A, B, and C. Areas to be included in the draft report will be determined at the kick-off meeting.

2. Five copies of the final report and three electronic copies on Tasks A, B, and C shall be submitted.

3. Government comments and recommendations will be provided to the A/E on the draft submittals for incorporation into the final report.

4. Final reports will be of professional quality including color maps, drawings, figures, and appendices. The A/E shall furnish the Base with an original manuscript and a diskette of the final submittals.

B. AutoCad mapping update

1. Five copies of the appropriate sheets (F-size prints) shall be submitted with the draft report.

2. The A/E shall submit for approval F-size prints showing the updated sheets of the water distribution system with

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a drawing scale of 1 inch = 200 feet.

      3. Ten sets of half size prints shall also be provided with the final report. Two copies of final mapping mylars, and one copy of final AutoCad drawing files on 1.44 M 3 1/2 inch diskette shall also be submitted.

   C.   Data coverages

   D.   GPS Tables

   E.   Geographic Information System (GIS) Specifications For Digital Data. Any maps, drawings, figures, sketches, databases, spreadsheets, or text files prepared for this contract shall be provided in both hard copy and digital form. The hard copy deliverables are defined in a previous section of this statement of work.

      1.   **Text, Spreadsheet, and Database Files:** The Marine Corps standard computing software is Microsoft Office. Final Reports and other text documents shall be provided in Microsoft Word 2000 format **AND** Adobe Portable Document Format (PDF). Spreadsheet files shall be provided in Microsoft Excel format. Databases shall be provided in Microsoft Access format, unless specified otherwise, as approved by the Government. **Prior to database development, the contractor shall provide the Government with a Technical Approach Document** for approval which describes the contractor's technical approach to designing and developing the database. All text, spreadsheet, and database files shall be delivered on 3.5 inch, high density diskettes or compact disk read-only memory (CD-ROM) with ISO-9660 format.

     a. **Maps, Drawings, Sketches:**

     (1) **Geographic Data Delivery Format:**

      (a) Digital geographic maps and the related digital information shall be developed using double precision and delivered in uncompressed ARC/INFO export file format (.e00) using ARC/INFO Release 7.2 or higher. ARC/INFO is a geographic information system software application produced by the Environmental Systems Research Institute of Redlands, California, and is the software used by Camp Lejeune's Integrated Geographic Information Repository (IGIR) System.

      (b) Digital geographic maps and the related digital information shall be usable on a Sun Sparc computer system

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using the Solaris 2.8 UNIX Operating System.   It shall be provided on
2.3 or 5 Gbyte, 8 mm magnetic data cartridge tape using UNIX TAR.
The tapes shall be
delivered with written documentation describing which tape archival
(tar) options were used, making recommendations for restoring the
data, and relating how much data is stored on the tape. Digital
information may alternatively be delivered on compact disk read-only
memory (CD-ROM) with ISO-9660 format.

                (c) Geographic data shall be provided in meters
and projected into the Universal Transverse Mercator (UTM) coordinate
system.   The maps shall use UTM Zone 18, the GRS 1980 spheroid and
the North American Datum 1983 (WGS-84).   No offsets shall be used.
Each map layer or coverage shall have a projection file.   Map or
drawing scales will be determined by the Contracting Officer's
Technical Representative.   Mapping accuracy for the agreed scales
will conform to the American Society for Photogrammetry and Remote
Sensing (ASPRS), "Accuracy Standards for Large-Scale Maps" and
"Interim Accuracy Standards for Large-Scale Maps" (ASPRS, 1991).
Copies of the ASPRS Accuracy Standards can be obtained by contacting:

          American Society for Photogrammetry and Remote
Sensing
          5410 Grosvenor Lane, Suite 210
          Bethesda, MD 20814-2160

ASPRS accuracy standards can also be found on the Internet at:

          http://www.asprs.org

                (d) Geographic data must be provided in a form
that does not require translation,
preprocessing, or postprocessing before being used in the IGIR
System.   However, the
Contractor shall consult with the Government (specifically the
Geographic Information Systems Branch) concerning the use of
alternative delivery formats such as AutoCAD Release 14 or higher to
provide design drawings, sketches, or figures.   The Government may
approve the use of AutoCAD when it is determined that the format will
not compromise the spatial accuracy or structure of the delivered
data and that the data will easily integrate with the IGIR System.
All digital files provided in AutoCAD shall be in the same projection
and use the same coordinate system, datum, and units as stated above,
and shall be provided on 3.5 inch, high density diskettes or CD-ROMs.

                (2) **Geographic Data Structure**: The Contractor
shall develop all geographic information in a structure consistent
with the Spatial Data Standards (SDS), Version 2.0, released in

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January, 2001, or a higher version if available at the time of this project. The Contractor shall consult with the Government concerning modifications or additions to the SDS. The Government may approve modifications to the Standard if it is determined that SDS does not adequately address subject datasets. Copies of the SDS may be obtained by contacting:

Director, U.S. Army Engineer Waterways Experiment Station

CADD/GIS Technology Center
Attn: CEWES-IM-DA/Smith
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Electronic copies of the Standards are also available from the CADD/GIS Technology Center's
Internet homepage at URL address:

http://tsc.wes.army.mil

(3) **Geographic Data Documentation**: For each digital file delivered containing geographic information (regardless of format), **the Contractor shall provide documentation** consistent with the "Content Standards for Digital Geospatial Metadata, June 1998" published by the Federal Geographic Data Committee. The documentation shall include but is not limited to the following: the name and description of the map layer or coverage, the source of the data and any related data quality information such as accuracy and time period of content, the type of data coverage (point, line, polygon, etc.), the field names of all attribute data and a description of each field name, the definition of all codes used in the data fields, the ranges of numeric fields and the meaning of these numeric ranges, the creation date of the map layer and the name of the person who created it. A point of contact shall be provided to answer technical questions. A metadata generation software, called Document.aml, is available from ESRI for use with ARC/INFO to help in the production of the required metadata and should be used. If document.aml is not used, the Contractor must insure that the .DOC, .ATT, .NAR and .REF INFO files delivered with the data layers are compatible with the document.aml process.   Copies of the FGDC metadata standard can be obtained by contacting:

FGDC Secretariat
c/o U.S. Geological Survey
590 National Center

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Reston, Virginia 22092
(703) 648-5514

FGDC metadata standards can also be found on the Internet at:

http://www.fgdc.gov

        (4) **Geographic Data Review:** The digital geographic maps, related data, and text documents shall be included for review in the draft and final contract submittals. The reviews shall include a visual demonstration of the geographic data on one of the Sun Sparc or Windows NT computer systems supported by the Geographic Information System (GIS) Branch, Business and Logistics Support Department. Actual installation of the digital data from the magnetic tape cartridge or CD-ROM onto the computer will be conducted by GIS Branch personnel. However, **the Contractor shall have a technical consultant available at each review to assist with any digital data discrepancies.** The data will be analyzed for subject content and system compatibility. Review comments to data and text shall be incorporated by the Contractor prior to approval of the final submittal.

        (5) **Ownership:** All digital files, final hard-copy products, source data acquired for this project, and related materials, including that furnished by the Government, shall become the property of Marine Corps Base, Camp Lejeune and will not be issued, distributed, or published by the Contractor.

      F. Global Positioning System (GPS) Data Collection Standards

      1. Field Procedures

        a. Static Mode - recommend 180+ measurements at 1 second intervals; measurements must be stored in the receiver for later downloading and post-processing.

        b. Kinematic mode - the time between measurements should not exceed 1 second.

        c. Elevation mask > 10 degrees.

        d. Datum - WGS 84 (Equivalent to NAD 83, the State legislated datum).

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e. Units – US Survey meters (NC General Statutes require US Survey Foot for English to metric conversion).

f. Elevation mode – Height above Ellipsoid (HAE).

g. PDOP < 6 with a minimum of four satellites.

h. The Roving (Field) Receiver must be within 200 miles of the approved Base Station to be used for differential corrections.

G. Equipment

1. The GPS receiver shall produce and store data in a format compatible with the Base station data used to perform the differential corrections.

2. Using differential GPS techniques, the GPS receiver shall be able to obtain accuracies of $\pm$ 0.5 meters or better.

3. GPS receiver shall have the capability to collect, store, and transfer digital data files that contain pseudo-range measurements with time epoch.

4. The North Carolina Geodetic Survey will maintain a list of receivers known to be compatible with the North Carolina Geodetic Survey Base Station Network.

H. Approved Based Stations

1. North Carolina Geodetic Survey Base Stations located at:
Washington – Regional Office EHNR
Asheville – Regional Office of EHNR
Raleigh – Archdale Building

2. The North Carolina Geodetic Survey will maintain a list of additional approved Base Stations and their geodetic control specifications.

VI. **ADDITIONAL INFORMATION**

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A.   The following information shall be made available for copy by the A/E after award but not later than the kick-off meeting:

1.   Historic As-built drawings of the water distribution systems will be made available.

2. GIS maps of the existing Hadnot Point and Holcomb water systems

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APPENDIX B

DIMENSIONS OF TREATMENT UNITS

AH Environmental Consultants

Plant Configuration in the period from 1968 to 1985			
	HOLCOMB BOULEVARD	**HADNOT POINT**	**TARRAWA TERRACE**
Building	670	20	TT38
Raw Water Reservoir	None	1	None
Capacity	n/a	800,000 gal	n/a
Width	n/a	95.00 ft	n/a
Length	n/a	95.00 ft	n/a
Bottom Elevation	n/a	15.00 ft	n/a
Top Elevation	n/a	26.75 ft	n/a
Depth	n/a	11.75 ft	n/a
Softeners	2	5	1
Type	Spiractor	Spiractor	Spiractor
Capacity	700 gpm	700 gpm	700 gpm
Top Radius	5.20 ft	5.20 ft	5.20 ft
Bottom Radius	1.20 ft	1.20 ft	1.20 ft
Outlet Elevation	n/a	34.50 ft	n/a
Bottom Elevation	n/a	15.50 ft	n/a
Approx. Depth	22.00 ft	22.00 ft	22.00 ft
Recarbonation Basin	None	1	None
Capacity	n/a	17,000 gal	n/a
Width	n/a	8.50 ft	n/a
Length	n/a	30.00 ft	n/a
Bottom Elevation	n/a	26.00 ft	n/a
Top Elevation	n/a	37.00 ft	n/a
Normal W.L.	n/a	35.00 ft	n/a
Depth	n/a	9.00 ft	n/a
Filters	2	5	6
Type	Gravity	Gravity	Pressure
Width (or Diameter)	18.00 ft	17.50 ft	9.00 ft
Length	20.00 ft	20.00 ft	n/a
Bottom Elevation	38.50 ft	26.00 ft	n/a
Filter Bottom Depth	1.83 ft	0.00 ft	n/a
Gravel	1.00 ft	1.50 ft	n/a
Sand	2.25 ft	2.25 ft	n/a
Normal W.L.	47.50 ft	35.00 ft	n/a
Normal Water Depth Over Media	3.92 ft	5.25 ft	n/a
Finished Water Clear Well 1	1	1	1
Capacity	1,000,000 gal	560,000 gal	750,000 gal
Width (or Diameter)	86.00 ft	79.00 ft	105.00 ft
Length	181.00 ft	79.00 ft	
Bottom Elevation (max.)	27.50 ft	15.00 ft	12.00 ft
Normal W.L.	36.50 ft	26.75 ft	24.00 ft
Approx. Depth	9.00 ft	12.00 ft	12.00 ft
Finished Water Clear Well 2		1	
Capacity		2,000,000 gal	
Width (or Diameter)		152.00 ft	
Length		152.00 ft	
Bottom Elevation (max.)			
Normal W.L.			
Approx. Depth		11.57 ft	
Built	1970	1942	1950 (Original Design)
Contract No.	N62470-70-B-0939	P-108-4	n/a
Drawing No.	NAVFAC 1338889-1338937	Y&D 162208 - 162275	DPW 40278
Significant Upgrades			
Year	1984-1987	1944	1962
Contract No.	N62470-81-B-1644	11255 Proj.No P-1514	n/a
Drawing	NAVFAC 4107534-4107607	PW 304-318	Y&D 859315-859322
Upgrades	Raw water reservoir, additional clearwell, 3 spiractors, 3 filters	2 spiractors, 2 filters, new 560,000-gallon clearwell	Added pressure filters
Year		1950-1953 ?	
Contract No.		?	
Drawing		?	
Upgrades		Added 2.0 MG clearwell	
Year		1959	
Contract No.		n/a	
Drawing		Y&D 842850 - 842862	
Upgrades		Converted original clearwell to raw water reservoir	

APPENDIX C

VOC REMOVAL CALCULATIONS

AH Environmental Consultants

Properties of Chemical	TCE	PCE
Henry's Constant (atm·m³/mol)	7.07E-03	1.31E-02
Molecular Weight	131.39	165.82
Wind Speed [m/s]	5	5
Geometry		
Top Radius [m]	1.6	1.6
Bottom Radius [m]	0.37	0.37
Height [m]	6.7	6.7
Volume [m³]	23.08	23.08
Surface Area [m²]	8.04	8.04
Hydraulics		
Flow Rate [m³/h]	157.73	157.73
Detention Time [h]	0.15	0.15
Overflow Rate [m/s]	0.01	0.01
Liquid Phase Exchange Coef.		
k_l (Equation 6) [cm/h]	0.11	0.09
Gas Phase Exchange Coef.		
k_g (Equation 4) [cm/h]	2107.41	1875.91
Liquid Mass Transfer Coefficient		
K_L (Equation 3) [cm/h]	0.11	0.09
Overall Volatilization Constant		
k_v (Equation 2) [1/h]	0.00	0.00
Half Life		
$t_{1/2}$ [d]	183.49	206.12
Fraction Remaining After Detention Time		
C_l/C_o	0.999976973	0.999979501
Removal		
$1-C_l/C_o$	0.00%	0.00%

Reference Substance Properties (Benzene)		
Diffusion Coefficient in Air D_{go} (cm^2/s)	0.0982	
Diffusion Coefficient in Water D_{lo} (cm^2/s)	8.99E-06	
Properties of Chemical	**TCE**	**PCE**
Henry's Constant (atm·m^3/mol)	7.07E-03	1.31E-02
Diffusion Coefficient in Water D_{lv} (cm^2/s)	8.43E-06	7.59E-06
Diffusion Coefficient in Air D_{gv} (cm^2/s)	0.089	0.0813
Molecular Weight M	131.39	165.82
Geometry		
Pipe Diameter [m]	0.3	0.3
Pipe Circumference [m]	0.94	0.94
Critical Depth above Weir * 1.5 [m]	0.05	0.05
Fall Height Z [m]	0.375	0.375
Tailwater Depth h [m]	0.15	0.15
Hydraulics		
Flow Rate [m^3/h]	157.73	157.73
Flow Rate per Length of Weir q [m^2/h]	167.79	167.79
Deficit Ratio		
ln(r) (Equation 11) [-]	0.1520	0.1520
Liquid Mass Transfer Coefficient		
k_l (Equation 10) [m/s]	0.0181	0.0169
Gas Mass Transfer Coefficient		
k_g (Equation 9) [m/s]	0.0469	0.0441
Overall Mass Transfer Coefficient		
K_o (Equation 8) [m/s]	7.82E-03	9.92E-03
Fraction Remaining		
C_l/C_o	0.9390	0.9233
Removal		
1-C_l/C_o	6.10%	7.67%

Hadnot Point Basins - TCE and PCE Removal

Properties of Chemical	Raw Water Reservoir		Recarbonation Basin	
	TCE	PCE	TCE	PCE
Henry's Constant (atm·m³/mol)	7.07E-03	1.31E-02	7.07E-03	1.31E-02
Molecular Weight	131.39	165.82	131.39	165.82
Wind Speed [m/s]	0	0	5	5
Geometry				
Width or Diameter [m]	28.96	28.96	2.59	2.59
Length [m]	28.96	28.96	9.14	9.14
Depth [m]	3.58	3.58	2.74	2.74
Volume [m³]	3002.82	3002.82	64.99	64.99
Surface Area [m²]	838.45	838.45	23.69	23.69
Cross-Sectional Area [m²]	103.70	103.70	7.11	7.11
Hydraulics				
Flow Rate [m³/h]	788.63	788.63	788.63	788.63
Detention Time [h]	3.81	3.81	0.08	0.08
Flow Velocity or Overflow Rate [m/s]	0.0021	0.0021	0.0308	0.0308
Liquid Phase Exchange Coef.				
k_l (Equation 5) [cm/h]	0.0126	0.0112	1.03	0.92
Gas Phase Exchange Coef.				
k_g (Equation 4) [cm/h]	0.8894	0.7917	2118.0956	1885.4206
Liquid Mass Transfer Coefficient				
K_L (Equation 3) [cm/h]	0.0120	0.0109	1.0298	0.9174
Overall Volatilization Constant				
k_v (Equation 2) [1/h]	0.0000	0.0000	0.0038	0.0033
Half Life				
$t_{1/2}$ [d]	862.36	948.32	7.69	8.64
Fraction Remaining After Detention Time				
C_i/C_o	0.999872486	0.999884044	0.99969069	0.999724453
Removal				
$1-C_i/C_o$	0.01%	0.01%	0.03%	0.03%

Hadnot Point Basins - TCE and PCE Removal

Properties of Chemical	Gravity Filter TCE	Gravity Filter PCE	Clearwell 1 TCE	Clearwell 1 PCE
Henry's Constant (atm·m³/mol)	7.07E-03	1.31E-02	7.07E-03	1.31E-02
Molecular Weight	131.39	165.82	131.39	165.82
Wind Speed [m/s]	0	0	0	0
Geometry				
Width or Diameter [m]	5.33	5.33	24.08	24.08
Length [m]	6.10	6.10	24.08	24.08
Depth [m]	1.60	1.60	3.66	3.66
Volume [m³]	52.03	52.03	2120.71	2120.71
Surface Area [m²]	32.52	32.52	579.81	579.81
Cross-Sectional Area [m²]	8.54	8.54	88.07	88.07
Hydraulics				
Flow Rate [m³/h]	157.73	157.73	788.63	788.63
Detention Time [h]	0.33	0.33	2.69	2.69
Flow Velocity or Overflow Rate [m/s]	0.0013	0.0013	0.0025	0.0025
Liquid Phase Exchange Coef.				
k_l (Equation 5) [cm/h]	0.0140	0.0124	0.0145	0.0129
Gas Phase Exchange Coef.				
k_g (Equation 4) [cm/h]	0.5673	0.5050	1.0472	0.9322
Liquid Mass Transfer Coefficient				
K_L (Equation 3) [cm/h]	0.0129	0.0119	0.0139	0.0126
Overall Volatilization Constant				
k_v (Equation 2) [1/h]	0.0001	0.0001	0.0000	0.0000
Half Life				
$t_{1/2}$ [d]	358.21	388.09	761.82	838.09
Fraction Remaining After Detention Time				
C_i/C_o	0.999973403	0.99997545	0.999898059	0.999907335
Removal				
$1-C_i/C_o$	0.00%	0.00%	0.01%	0.01%

	Clearwell 2	
Properties of Chemical	**TCE**	**PCE**
Henry's Constant (atm·m³/mol)	7.07E-03	1.31E-02
Molecular Weight	131.39	165.82
Wind Speed [m/s]	0	0
Geometry		
Width or Diameter [m]	46.33	46.33
Length [m]	46.33	46.33
Depth [m]	3.53	3.53
Volume [m³]	7569.47	7569.47
Surface Area [m²]	2146.43	2146.43
Cross-Sectional Area [m²]	163.38	163.38
Hydraulics		
Flow Rate [m³/h]	788.63	788.63
Detention Time [h]	9.60	9.60
Flow Velocity or Overflow Rate [m/s]	0.0013	0.0013
Liquid Phase Exchange Coef.		
k_l (Equation 5) [cm/h]	0.0082	0.0073
Gas Phase Exchange Coef.		
k_g (Equation 4) [cm/h]	0.5645	0.5025
Liquid Mass Transfer Coefficient		
K_L (Equation 3) [cm/h]	0.0078	0.0071
Overall Volatilization Constant		
k_v (Equation 2) [1/h]	0.0000	0.0000
Half Life		
$t_{1/2}$ [d]	1306.96	1436.50
Fraction Remaining After Detention Time		
C_i/C_o	0.999787919	0.999807043
Removal		
$1-C_i/C_o$	0.02%	0.02%

Properties of Chemical	Gravity Filter		Clearwell	
	TCE	PCE	TCE	PCE
Henry's Constant (atm·m³/mol)	7.07E-03	1.31E-02	7.07E-03	1.31E-02
Molecular Weight	131.39	165.82	131.39	165.82
Wind Speed [m/s]	0	0	0	0
Geometry				
Width or Diameter [m]	5.49	5.49	26.21	26.21
Length [m]	6.10	6.10	55.17	55.17
Depth [m]	1.19	1.19	2.74	2.74
Volume [m³]	39.96	39.96	3967.02	3967.02
Surface Area [m²]	33.45	33.45	1446.13	1446.13
Cross-Sectional Area [m²]	6.56	6.56	71.91	71.91
Hydraulics				
Flow Rate [m³/h]	157.73	157.73	315.45	315.45
Detention Time [h]	0.25	0.25	12.58	12.58
Flow Velocity or Overflow Rate [m/s]	0.0013	0.0013	0.0012	0.0012
Liquid Phase Exchange Coef.				
k_l (Equation 5) [cm/h]	0.0166	0.0147	0.0088	0.0079
Gas Phase Exchange Coef.				
k_g (Equation 4) [cm/h]	0.5515	0.4909	0.5131	0.4567
Liquid Mass Transfer Coefficient				
K_L (Equation 3) [cm/h]	0.0150	0.0140	0.0083	0.0076
Overall Volatilization Constant				
k_v (Equation 2) [1/h]	0.0001	0.0001	0.0000	0.0000
Half Life				
$t_{1/2}$ [d]	229.62	246.95	950.13	1040.21
Fraction Remaining After Detention Time				
C_l/C_o	0.999968134	0.99997037	0.999617807	0.9996509
Removal				
$1-C_l/C_o$	0.00%	0.00%	0.04%	0.03%

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	Clearwell	
Properties of Chemical	**TCE**	**PCE**
Henry's Constant (atm·m³/mol)	7.07E-03	1.31E-02
Molecular Weight	131.39	165.82
Wind Speed [m/s]	0	0
Geometry		
Width or Diameter [m]	32.00	32.00
Length [m]		
Depth [m]	3.66	3.66
Volume [m³]	2942.35	2942.35
Surface Area [m²]	804.45	804.45
Cross-Sectional Area [m²]	117.06	117.06
Hydraulics		
Flow Rate [m³/h]	157.73	157.73
Detention Time [h]	18.65	18.65
Flow Velocity or Overflow Rate [m/s]	0.0004	0.0004
Liquid Phase Exchange Coef.		
k_l (Equation 5) [cm/h]	0.0023	0.0021
Gas Phase Exchange Coef.		
k_g (Equation 4) [cm/h]	0.1576	0.1403
Liquid Mass Transfer Coefficient		
K_L (Equation 3) [cm/h]	0.0022	0.0020
Overall Volatilization Constant		
k_v (Equation 2) [1/h]	0.0000	0.0000
Half Life		
$t_{1/2}$ [d]	4787.05	5259.86
Fraction Remaining After Detention Time		
C_l/C_o	0.999887458	0.999897574
Removal		
$1-C_l/C_o$	0.01%	0.01%